



FCNC Charm Decays

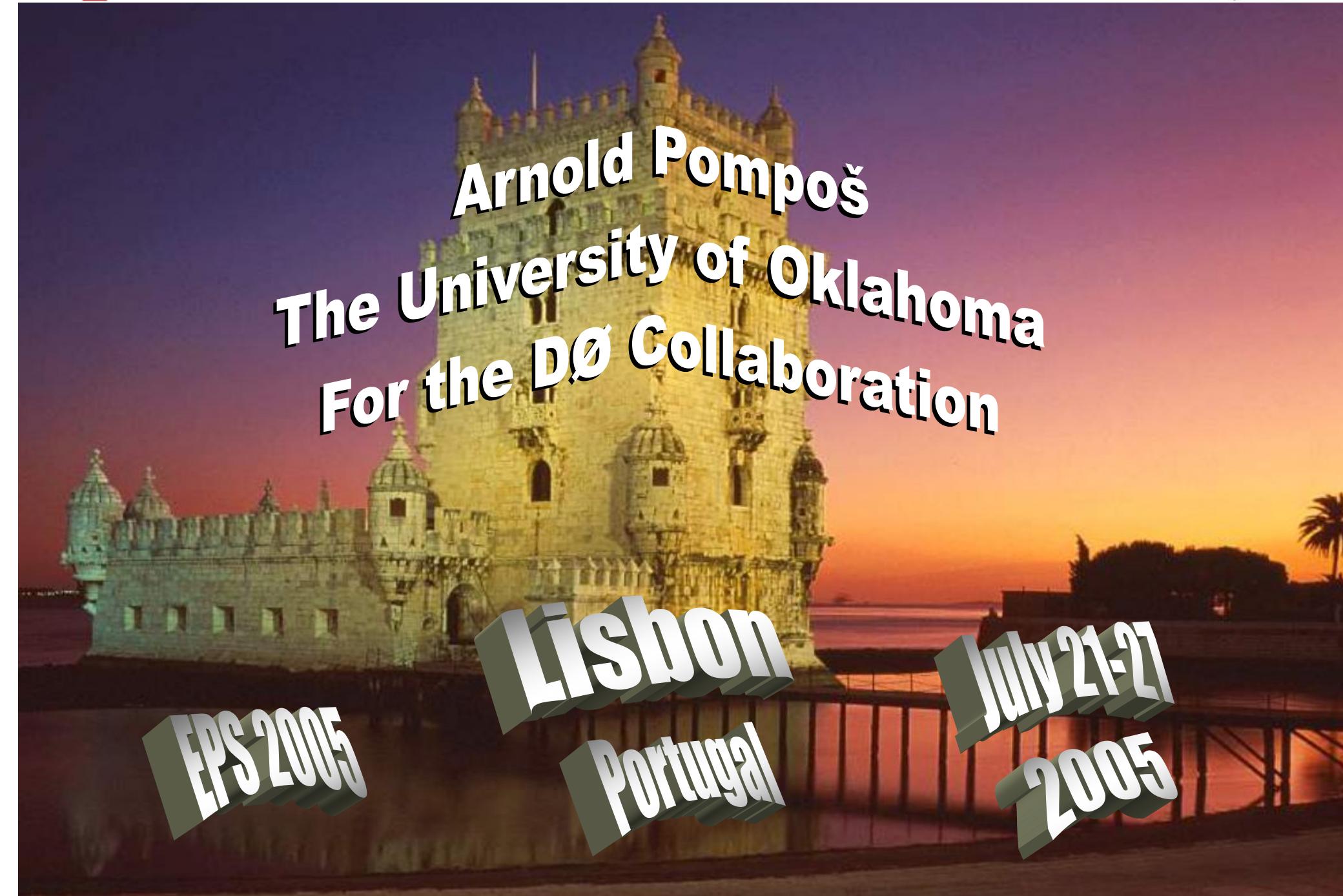


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For the DØ Collaboration

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Portugal

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2005





Outline



In this talk we report on Flavor Changing Neutral Current
Charm Decays & Observation of $D_s^\pm \rightarrow \phi\pi^\pm \rightarrow \mu^+\mu^-\pi^\pm$

- Motivation for FCNC searches
- Analysis strategy
- Production and selection of D_s^\pm and D^\pm mesons
- Background reduction strategy
- D_s^\pm & D^\pm signal enhancing strategy
- D_s^\pm & D^\pm signal extraction
- Results
- Conclusion

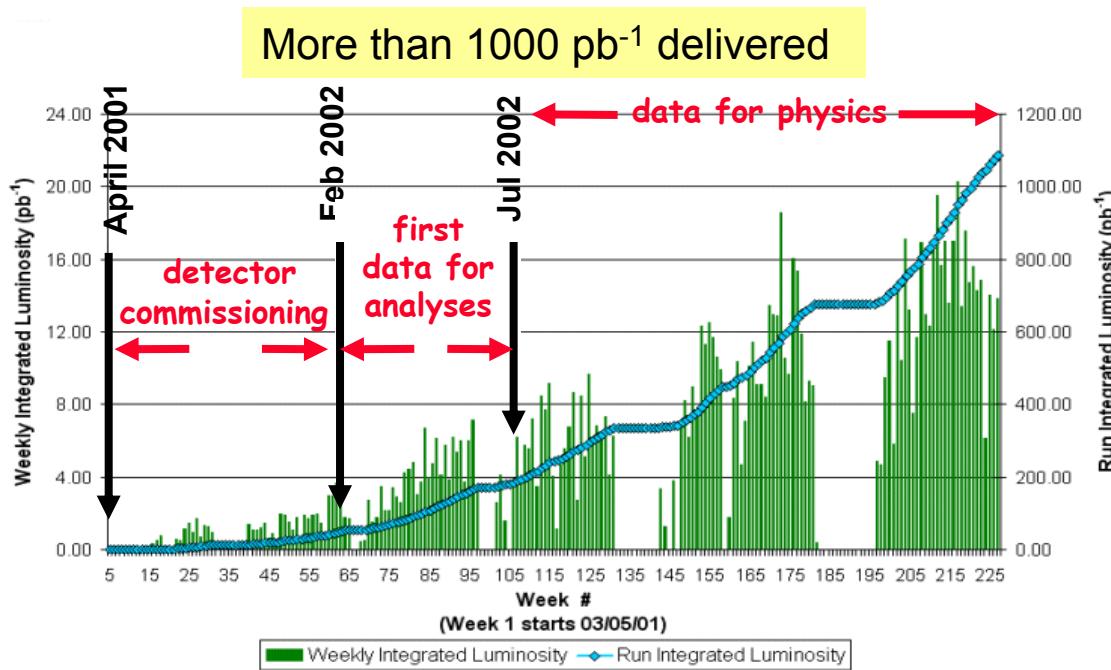




Tevatron - $p\bar{p}$ collider



- Run I (1992 - 1995) $\sqrt{s} = 1.8 \text{ TeV}$
 - delivered $\sim 260 \text{ pb}^{-1}$
- Run II (2002 - ong.) $\sqrt{s} = 1.96 \text{ TeV}$
 - collisions every 396 ns
 - rate to tape 50 Hz
 - delivers $\sim 10 \text{ pb}^{-1}/\text{week}$



- High data taking efficiency
 - in the range 80-90%
- So far analyzed
 - Above 500 pb⁻¹
 - 5x the total Run I data

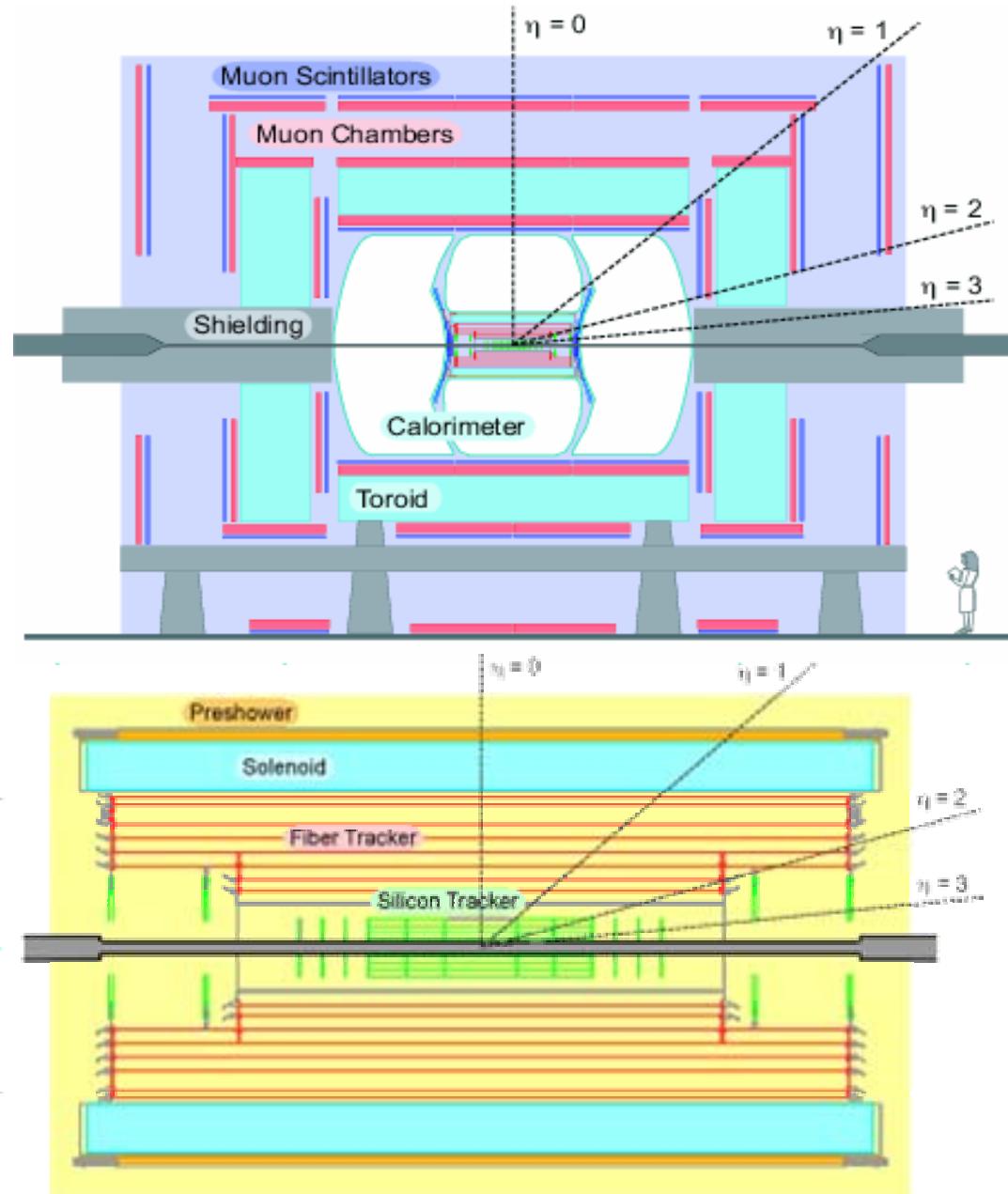




The DZero Experiment



- Beamline shielding
 - Reduces accelerator background
- Silicon tracker
 - Coverage up to $|\eta| < 2$
- Fiber tracker
 - 8 double layers
 - Coverage up to $|\eta| < 2$
- Solenoid (2 Tesla)
- Forward + central muon system
 - Coverage up to $|\eta| < 2$
- Three level trigger system
 - Outputs 50 Hz



➤ For every rare SM process there is a "beyond the SM" theory in which it is enhanced.

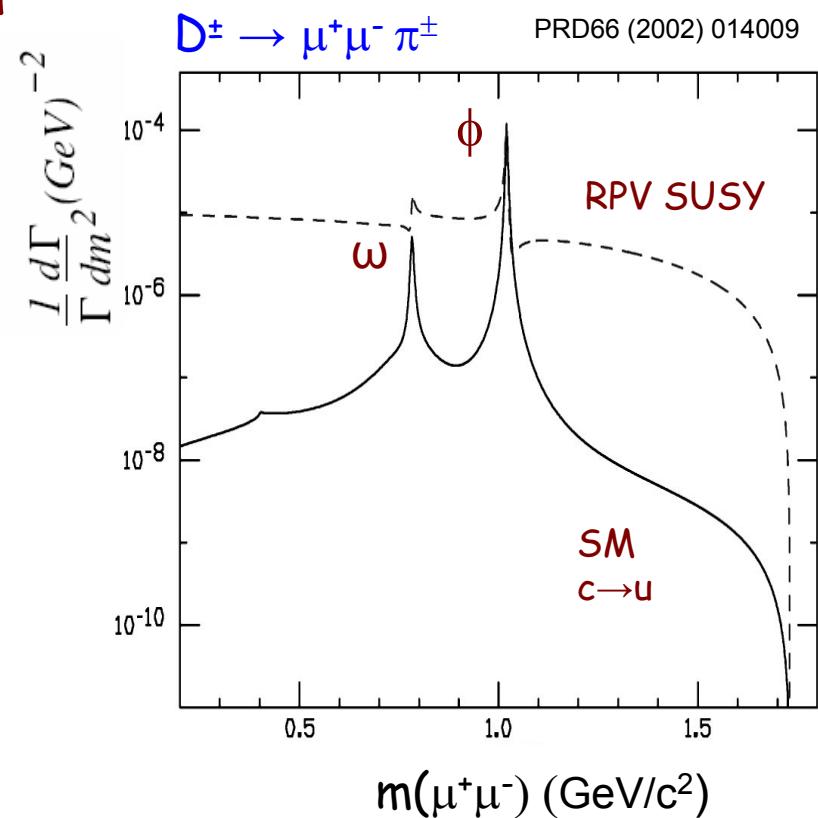
- RPV SUSY can enhance SM suppressed FCNC processes.

➤ FCNC processes with down type quarks

- $s \rightarrow d$ type studied with kaons (K^\pm, K^0)
- $b \rightarrow s$ type studied with B mesons.

➤ FCNC processes with up type quarks

- Still lot of room for new results
- In this talk we focus on $c \rightarrow u$ transitions

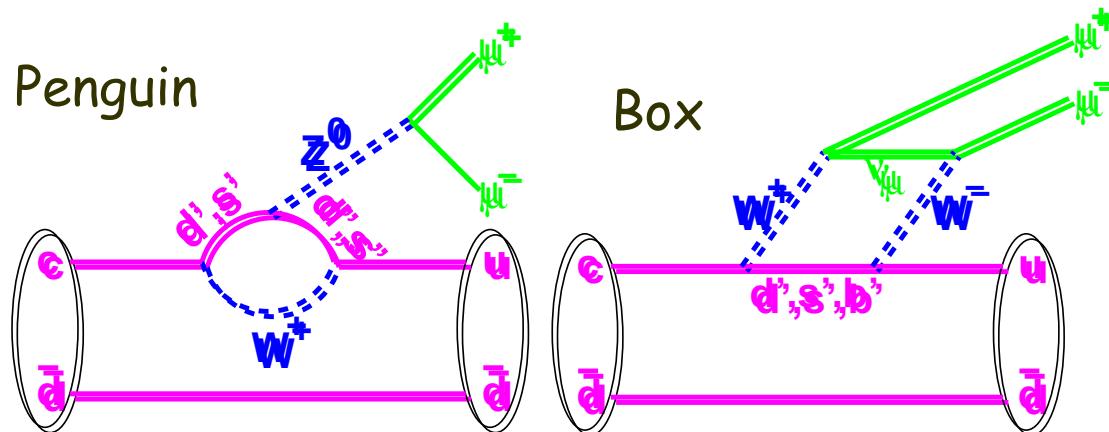


FCNC $c \rightarrow u$ transitions with D^\pm & D_s^\pm



$$D^\pm \rightarrow \mu^+ \mu^- \pi^\pm$$

➤ Non-resonant decays
(GIM suppressed, $\text{Br} \sim 10^{-8}$)



$$D_s^\pm \rightarrow \mu^+ \mu^- \pi^\pm$$

➤ Non-resonant decays
(Penguin & Box diagrams absent)

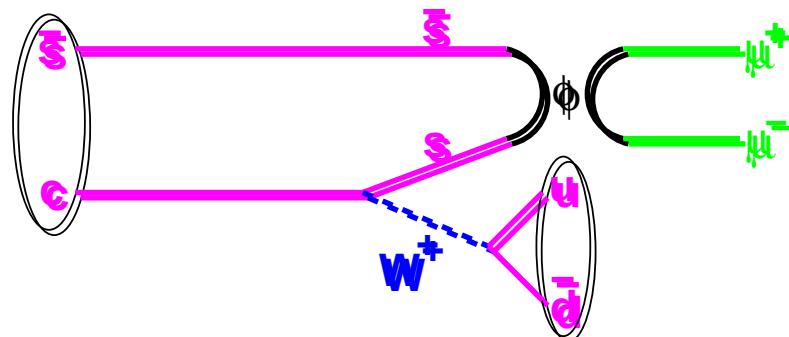
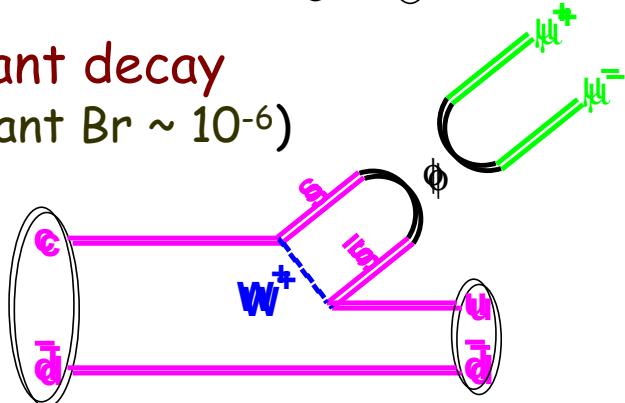
➤ Resonant decay
(Analogous to $b \rightarrow sl^+l^-$ studies after $B^\pm \rightarrow K^\pm J/\psi \rightarrow K^\pm \mu^+\mu^-$ observation)

- Observation = essential step to study $c \rightarrow ul^+l^-$ FCNC transitions

$$\text{Br}(D_s^\pm \rightarrow \phi \pi^\pm) \\ (3.6 \pm 0.9) \times 10^{-2}$$

$$\text{Br}(\phi \rightarrow \mu^+ \mu^-) \\ (2.85 \pm 0.19) \times 10^{-4}$$

➤ Resonant decay
(Dominant $\text{Br} \sim 10^{-6}$)



Analysis Strategy

- Observe resonant D_s^\pm and D^\pm decays
- Search non-resonant continuum for excess events





Production of D^\pm and D_s^\pm



- In $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV $\sigma(p\bar{p} \rightarrow c\bar{c}) \sim$ microbarns
- D_s^\pm production mechanisms at the Tevatron:
 - Prompt production: $p\bar{p} \rightarrow c\bar{c} \rightarrow D_s^\pm + X$
 - Secondary production: $p\bar{p} \rightarrow b\bar{b} \rightarrow B + X \rightarrow D_s^\pm + Y + X$
- We are interested in $D_s^\pm \rightarrow \mu^+ \mu^- \pi^\pm \Rightarrow$ we employ dimuon triggers
 - recording rate ~ 2 Hz
- D_s^\pm and D^\pm decay products tend to be within a narrow jet



D^\pm selection philosophy

Look for events with μ^+ , μ^- & a π^\pm track located within the same jet.

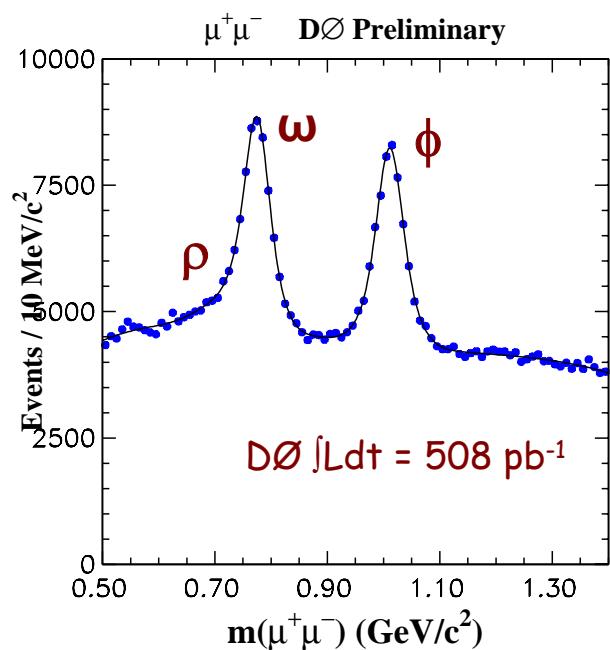


Muon, Track, D^\pm and D_s^\pm Selection



➤ Muon selection

- Two OS μ candidate each matched to a central track of $pT > 2 \text{ GeV}/c$
- Muons are within the same jet and coming from the same vertex
- $0.96 < m(\mu^+\mu^-) < 1.06 \text{ GeV}/c^2$



➤ π^\pm track selection

- Track in the same jet as $\mu^+\mu^-$ pair.
- Track from the same vertex as the $\mu^+\mu^-$ pair.

➤ D_s^\pm and D^\pm selection

- $\mu^+\mu^-$ & π^\pm track form a good vertex.
- $1.3 < m(\mu^+\mu^- \pi^\pm) < 2.5 \text{ GeV}/c^2$
- $\vec{p}(\mu^+\mu^- \pi^\pm)$ in the $\overrightarrow{\text{SV}} - \overrightarrow{\text{PV}}$ direction

Large track multiplicity yields several D_s^\pm or D^\pm candidates/event



Need better π^\pm track selection method



π^\pm track selection strategy



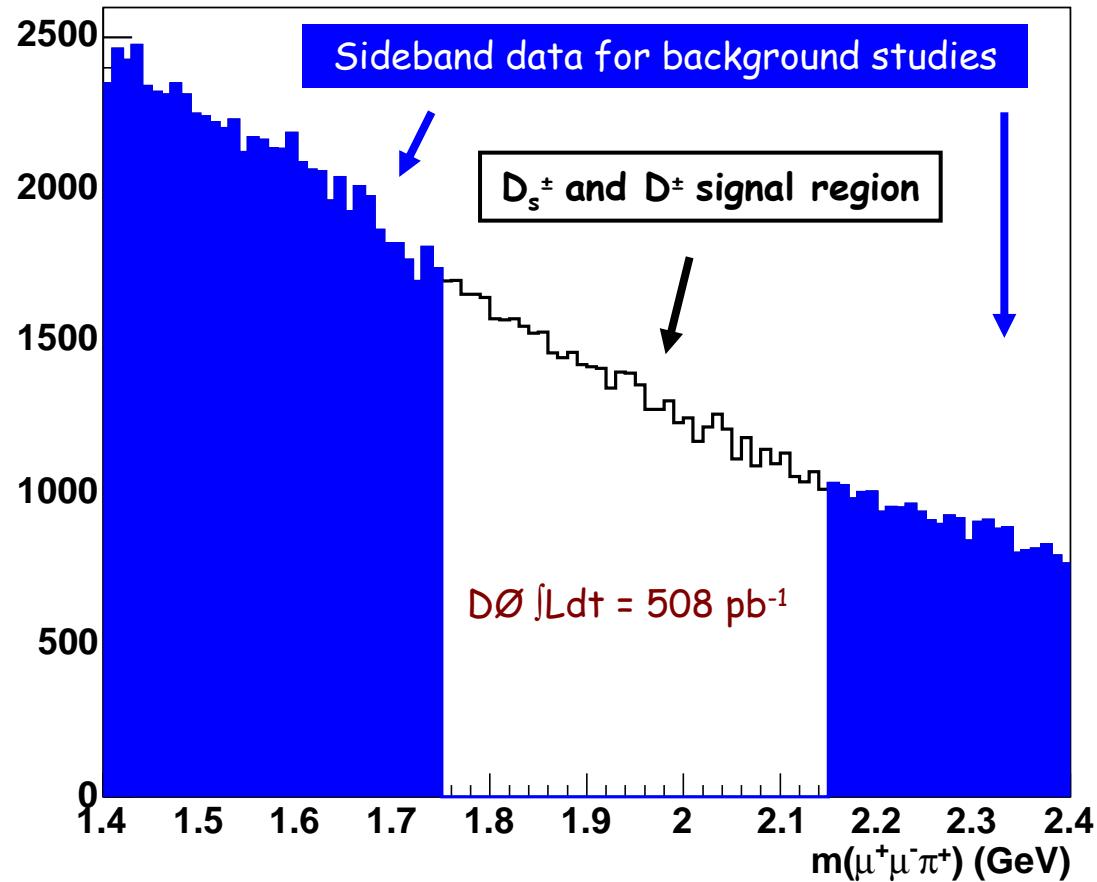
- MC studies showed that the correct π^\pm track:

- Forms a good vertex with the $\mu^+\mu^-$ system
- Has typically higher pT
- Is close to $\mu^+\mu^-$ in φ - η space ($\Delta R^2 = \Delta\eta^2 + \Delta\varphi^2$)

- We choose the π^\pm track which minimizes

$$M = \chi_{\text{vtx}}^2 + 1 \text{ GeV/pT}(\pi)^2 + \Delta R_\pi^2$$

- This strategy picks 90% times the right π^\pm track (in MC events)



Can you see the D_s^\pm or D^\pm ? ☺



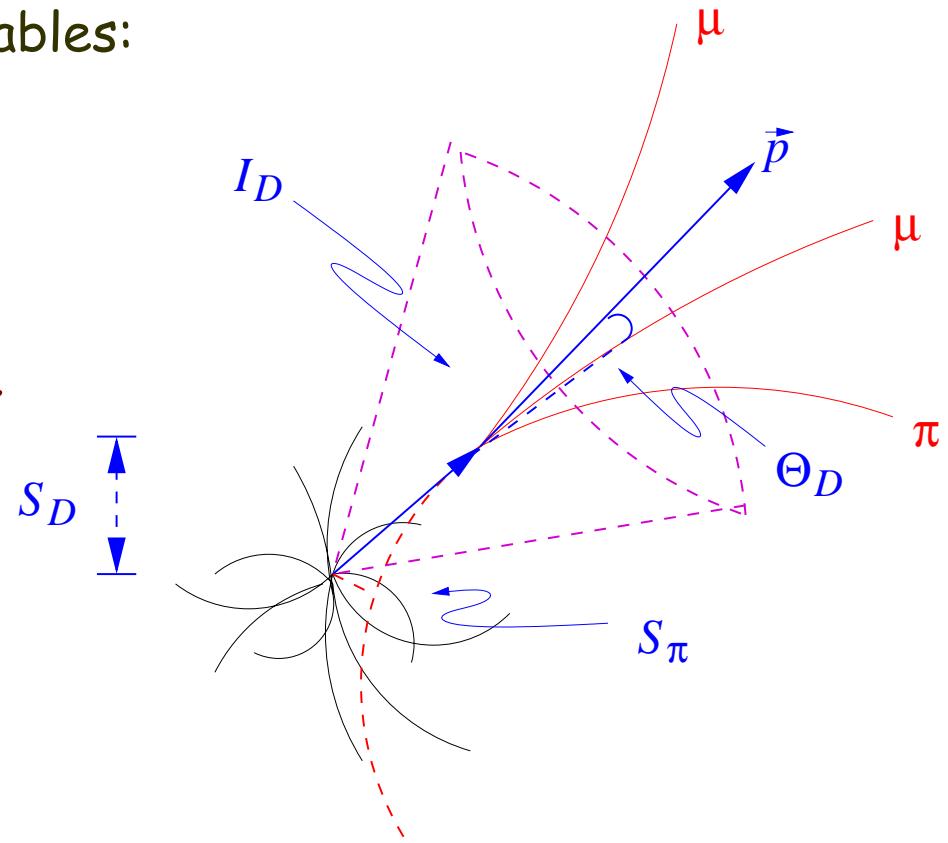


Background Suppression

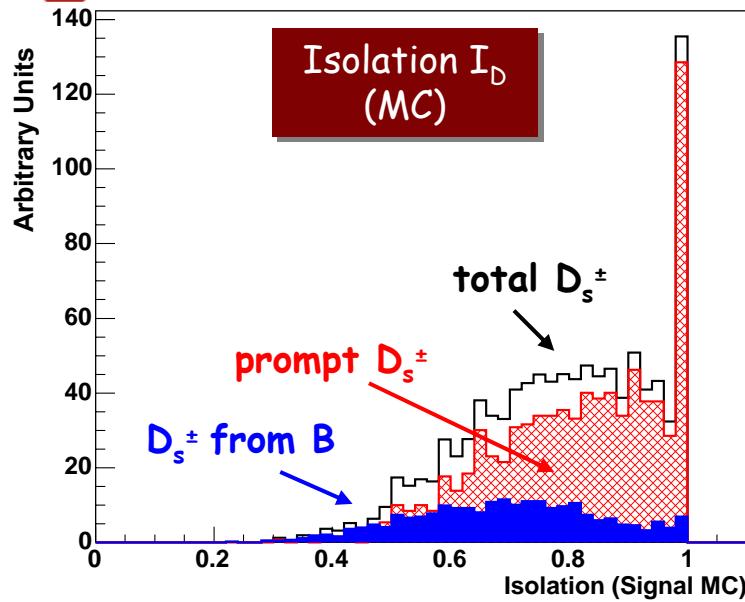


To minimize background, we employ 4 variables:

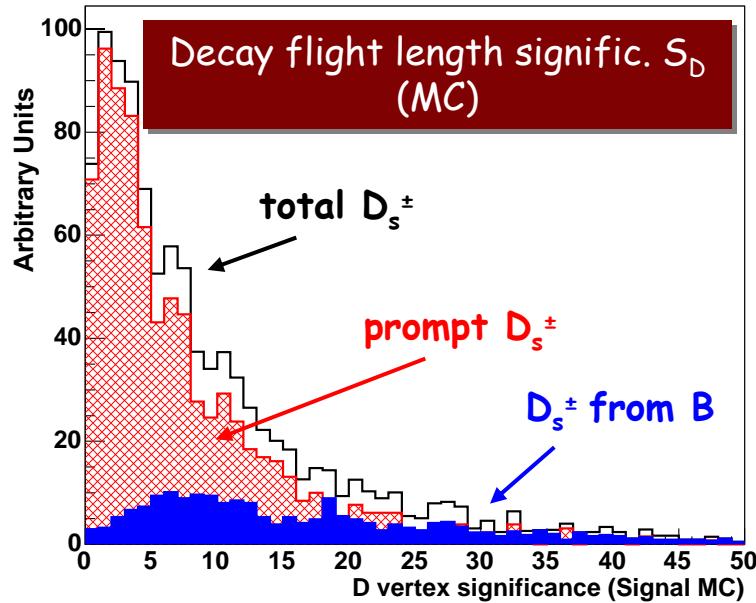
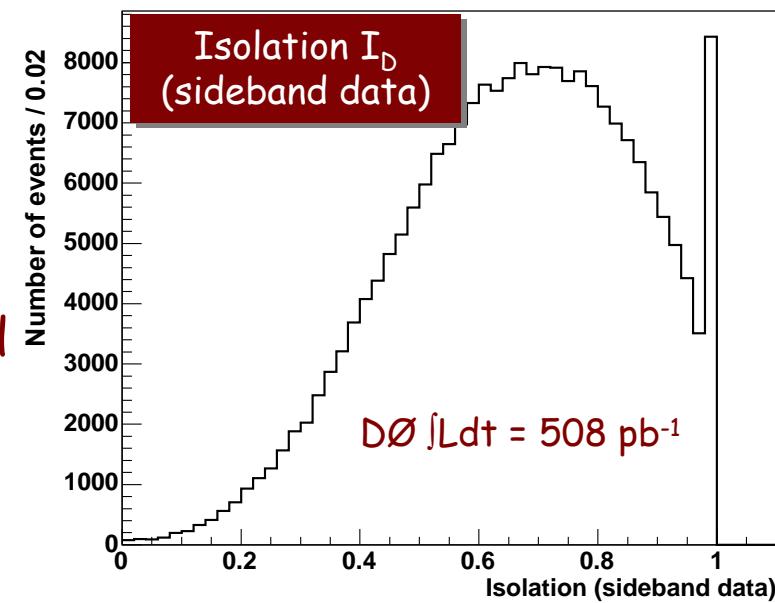
- I_D : tracking isolation of D_s^\pm
 - $I_D = p(D)/\sum p(\text{cone})$, cone $\Delta R < 1$
- S_D : transverse flight length significance of D_s^\pm
 - $S_D = L_{xy}/\sigma(L_{xy})$
- Θ_D : collinearity angle
 - Angle between \overrightarrow{SV} - \overrightarrow{PV} and $\overrightarrow{p}(D_s^\pm)$
- R_D : ratio of π^\pm impact parameter significance to S_D
 - $R_D = (\text{IP}_\pi/\sigma(\text{IP}_\pi))/S_D$



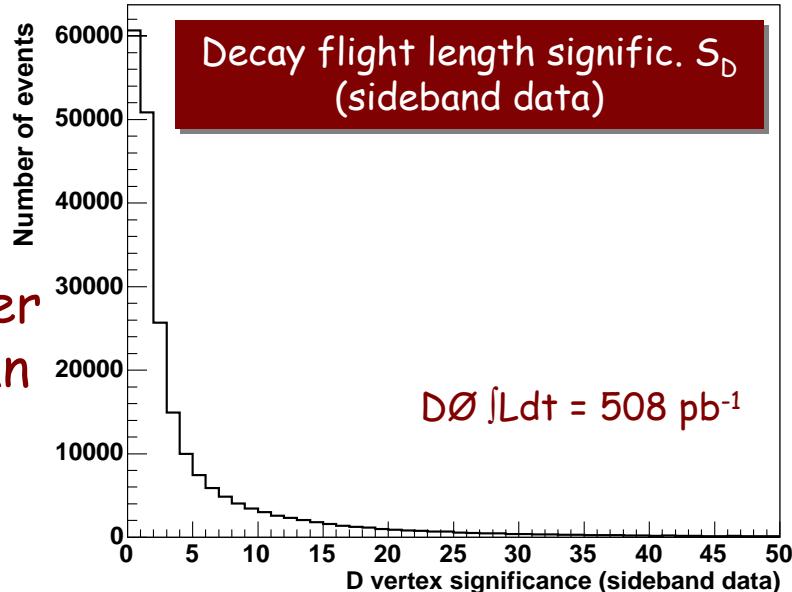
Backg. Suppression Variables-Example



➤ Prompt signal better isolated than background



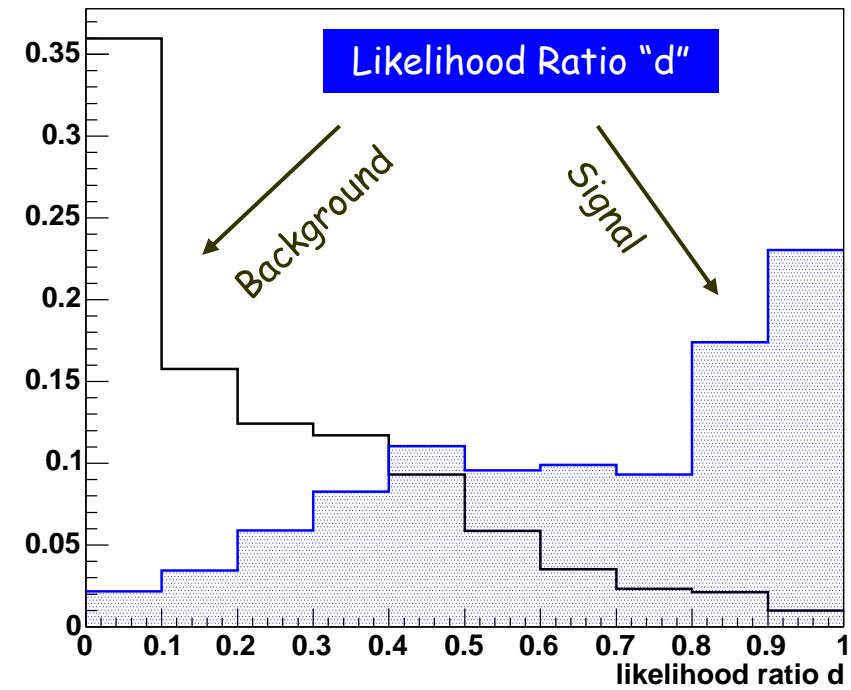
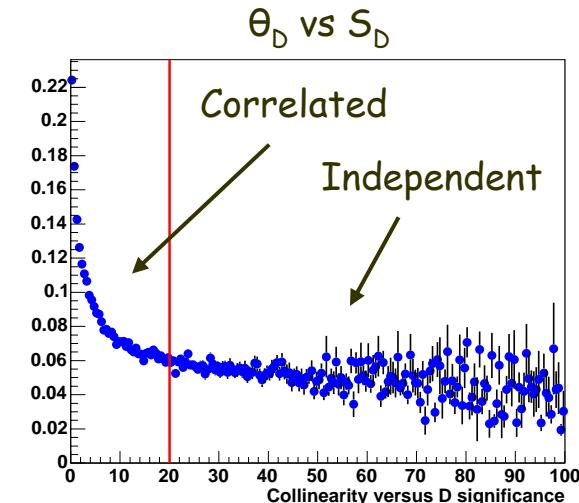
➤ Signal has higher significance than background



Combined Likelihood Variable



- No box cuts, use likelihood variables to extract D_s^\pm and D^\pm
- Isolation I_D is independent of S_D, θ_D & R_S
- S_D, θ_D & R_S are independent if SV well separated from PV
- Combined likelihood “ \mathcal{L} ” reflecting correlations:
 - $\mathcal{L} = \mathcal{L}(I_D) \times \mathcal{L}(S_D, \theta_D, R_S)$ if $S_D < 20$
 - $\mathcal{L} = \mathcal{L}(I_D) \times \mathcal{L}(S_D) \times \mathcal{L}(\theta_D) \times \mathcal{L}(R_S)$ if $S_D > 20$
- Plot likelihood ratio “d” :
 - $d = \mathcal{L}(\text{Signal}) / (\mathcal{L}(\text{Signal}) + \mathcal{L}(\text{Background}))$





Results: D_s^\pm observation



- Good agreement of "d" between MC and Data
- Keep events with $d > 0.9$
 - optimizes $\epsilon(\text{signal})/\sqrt{\epsilon(\text{backg})}$

Result I.

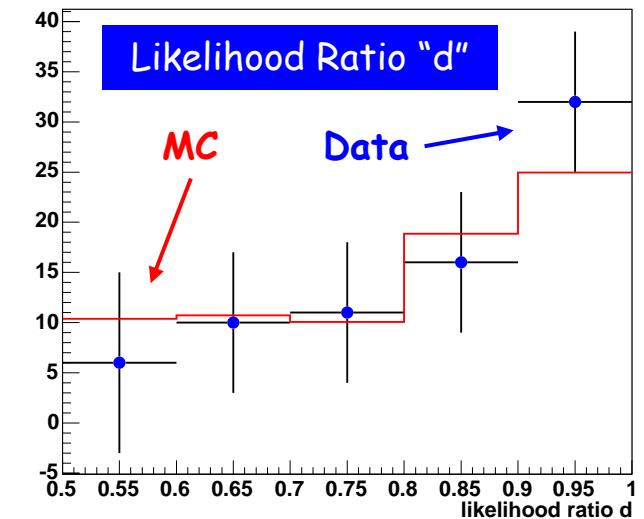
- In the D_s^\pm region $1.91 < m(\mu^+\mu^-\pi^\pm) < 2.03 \text{ GeV}/c^2$
 - 51 events found
 - 18 ± 4 background events expected



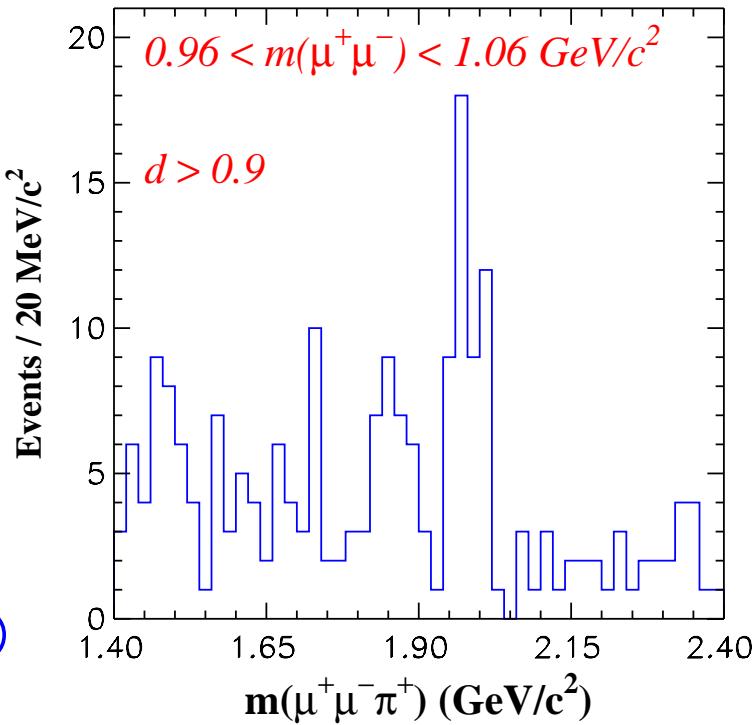
$31 \pm 7 D_s^\pm$ events observed

(corresponds to $> 7\sigma$ significance)

Nice, but how to extract the D^\pm ? ☹



$D \rightarrow \phi \pi^+ \rightarrow \pi^+ \mu^+ \mu^-$ DØ Preliminary





Results: D^\pm extraction



- Relax cut on likelihood ratio to 0.75
- Fit 2 Gaussians (signal) & exponential (background)

- Floating $\mu(D_s^\pm)$, $\sigma(D_s^\pm)$
- Fix $\mu(D_s^\pm) - \mu(D^\pm)$ to 1.969-1.864 GeV
- Fix $\sigma(D^\pm)$ to $m(D^\pm)/m(D_s^\pm) \times \sigma(D_s^\pm)$

Result II.

- In $1.91 < m(\mu^+\mu^-\pi^\pm) < 2.03 \text{ GeV}/c^2$, $d > 0.75$

51^{+12}_{-11} D_s^\pm events observed

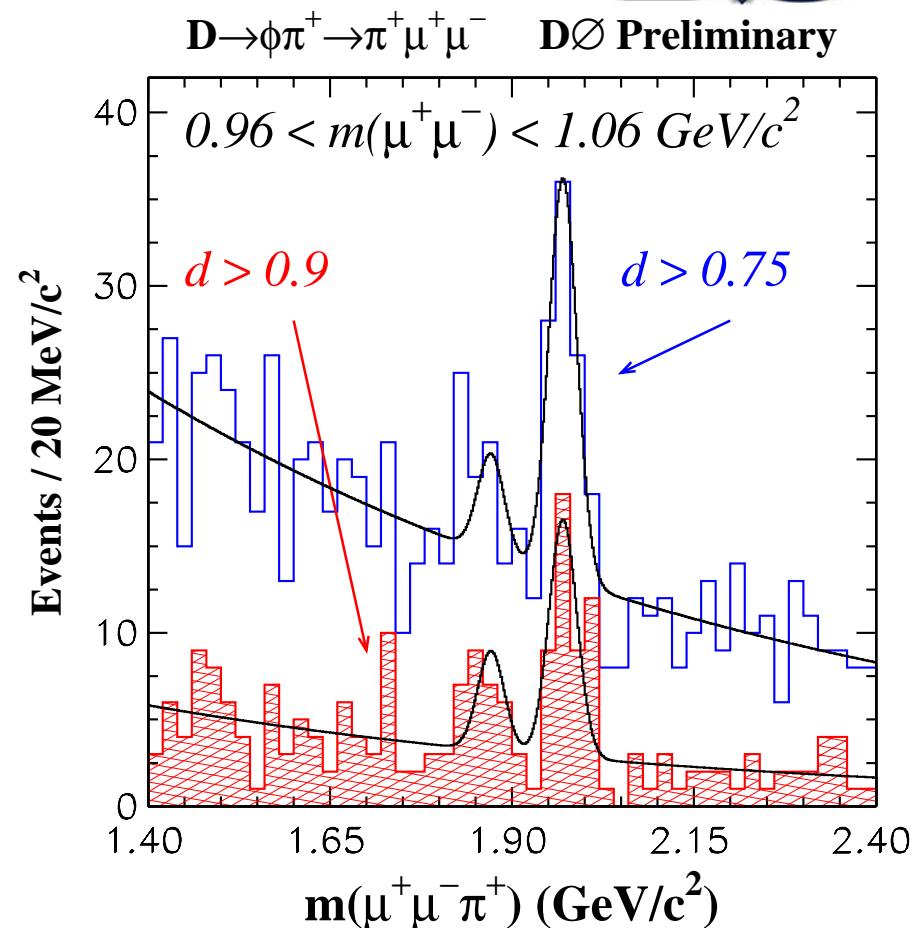
Result III.

- Use the above found $\mu(D_s^\pm)$, $\sigma(D_s^\pm)$ and fit the $d > 0.9$ distribution

$13.2^{+5.6}_{-4.9}$ D^\pm events observed

(corresponds to $> 2.7\sigma$ significance)

Nice, but need more data for observation ☺. Let's set a limit on D^\pm production!



Result: $\text{Br}(D^\pm \rightarrow \pi^\pm \mu^+ \mu^-)$ limit



$$\frac{\text{Br}(D^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm)}{\text{Br}(D_s^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm)} = \frac{N(D^\pm; d > 0.9)}{N(D_s^\pm; d > 0.75)} \times \frac{f(D_s^\pm)}{f(D^\pm)} \times \frac{\varepsilon(D_s^\pm; d > 0.75)}{\varepsilon(D^\pm; d > 0.9)}$$

Measured or
Limit Setting

To determine PDG Literature From MC

Result IV.

$$\frac{\text{Br}(D^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm)}{\text{Br}(D_s^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm)} = 0.17^{+0.08 +0.06}_{-0.07 -0.07}$$



$$\text{Br}(D^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm) = (1.70^{+0.79 +0.76}_{-0.73 -0.82}) \times 10^{-6}$$

Result V.

$$\frac{\text{Br}(D^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm)}{\text{Br}(D_s^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm)} < 0.28 \quad (\text{at } 90\% \text{ C.L.})$$



$$\text{Br}(D^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm) < 3.14 \times 10^{-6} \quad (\text{at } 90\% \text{ C.L.})$$



Conclusion



- We searched 508 pb^{-1} of DØ's dimuon sample and observed clear signal in $D_s^\pm \rightarrow \phi\pi^\pm \rightarrow \mu^+\mu^- \pi^\pm$ channel
- We set a 90% C.L. upper limit $\text{Br}(D^\pm \rightarrow \phi\pi^\pm \rightarrow \mu^+\mu^- \pi^\pm) < 3.14 \times 10^{-6}$



- DØ has great sensitivity to study FCNC in charm decays and we now continue to search the non-resonant continuum for signs of physics going beyond the Standard Model.
- Tevatron is doubling the luminosity each year → MORE GREAT PHYSICS RESULTS are coming soon & even more in few years ☺.

Flavor Changing Neutral Currents (for non-Experts)

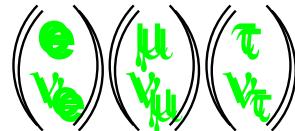


Weak Interactions - Part I.

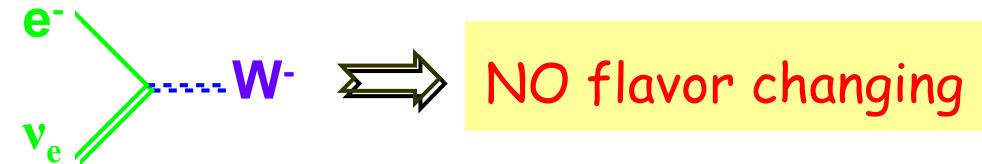


Charged Current (W^\pm mediated)

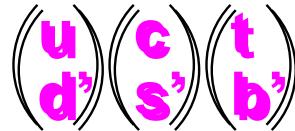
➤ Lepton flavors:



- W^\pm couples within the same generation



➤ Quark flavors:



where $\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \text{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$ mixes generations

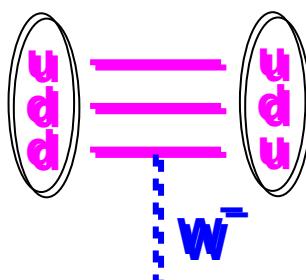
- W^\pm couples up with primed down



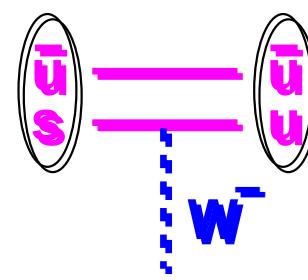
• Example:



ud coupling
strength $\sim \cos\theta_c$
95% of G_F



us coupling
strength $\sim \sin\theta_c$
5% of G_F



Neutral Current (Z^0 mediated)

- If the world had only u & $d' = d\cos\theta_c + s\sin\theta_c$, then neutral current would be:
 $(u, d') \times (\bar{u}, \bar{d}')^\top = u\bar{u} + d'\bar{d}' = u\bar{u} + d\bar{d}\cos^2\theta_c + s\bar{s}\sin^2\theta_c + (d\bar{s} + s\bar{d})\cos\theta_c\sin\theta_c$ (non zero!)

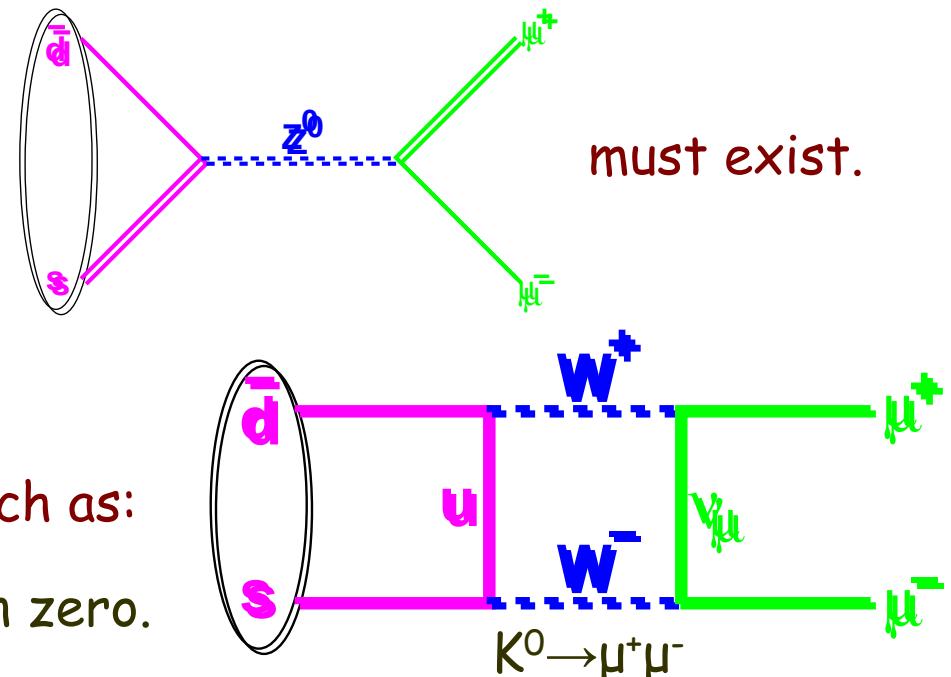
- If Z^0 coupled to uu or $d'd'$ then $K^0 \rightarrow \mu^+\mu^-$

But in the Standard Model it does not.

- What about higher order corrections, such as:

- The amplitude $M \sim +\cos\theta_c\sin\theta_c \Rightarrow$ non zero.

But this process does not occur in experimental data. Why?

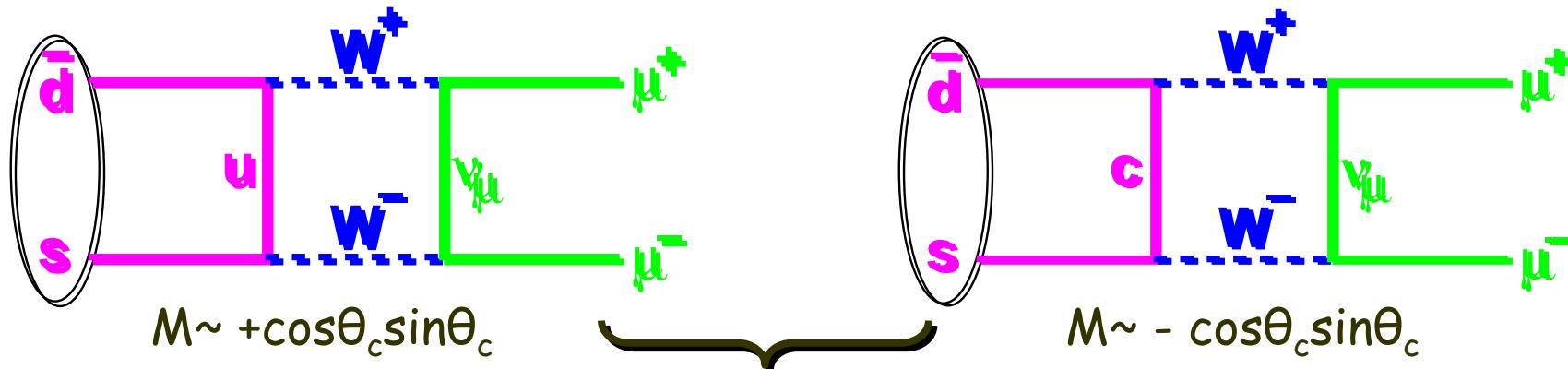


GIM mechanism

- Glashow, Iliopoulos & Maiani proposed the existence of the "c" quark.
- Then the neutral current out of two doublets $(\begin{matrix} u \\ d \end{matrix}) (\begin{matrix} c \\ s \end{matrix})$ is:

$$J^0 = uu + d'd' + cc + s's' = uu + dd + cc + ss \Rightarrow \text{No flavor changing terms exist}$$

Due to the proposed "c" quark, the $K^0 \rightarrow \mu^+ \mu^-$ process has two diagrams:



Cancelation = explains low rate in data

NOTE: Cancellation not exact due to different u and c masses. This allows to predict the c mass based on observed rates.

Backup Slides

Result: $\text{Br}(D^\pm \rightarrow \pi^\pm \mu^+ \mu^-)$ limit



$$\frac{\text{Br}(D^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm)}{\text{Br}(D_s^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm)} = \frac{N(D^\pm; d > 0.9)}{N(D_s^\pm; d > 0.75)} \times \frac{f(D_s^\pm)}{f(D^\pm)} \times \frac{\varepsilon(D_s^\pm; d > 0.75)}{\varepsilon(D^\pm; d > 0.9)}$$

To determine PDG From Limit Setting Literature From MC

➤ 90% C.L. upper limit on $\text{Br}(D^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm)$ found by: $\frac{\int_0^{\text{UL}} dr \mathcal{L}(r)}{\int_0^{\infty} dr \mathcal{L}(r)} = 0.9$, where $r = \frac{N(D^\pm; d > 0.9)}{N(D_s^\pm; d > 0.75)}$

Result IV.

$$\frac{\text{Br}(D^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm)}{\text{Br}(D_s^\pm \rightarrow \phi \pi^\pm \rightarrow \mu^+ \mu^- \pi^\pm)} < 0.28 \text{ (at 90% C.L.)}$$



$$\text{Br}(D^\pm \rightarrow \pi^\pm \mu^+ \mu^-) < 3.14 \times 10^{-6} \text{ (at 90% C.L.)}$$

Uncertainties summary

| | |
|---|------------|
| Statistical | +47, -43 % |
| Fitting | +14%, -24% |
| $f(D_s^\pm)$ | 26% |
| $f(D^\pm)$ | 8% |
| $\varepsilon(D_s^\pm)/\varepsilon(D^\pm)$ | 19% |
| $\text{Br}(D_s^\pm \rightarrow \phi \pi^\pm)$ | 25% |
| $\text{Br}(\phi \rightarrow \mu^+ \mu^-)$ | 7% |

